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# TITLE THE SHOCK HUGONIOT OF 316 SS AND SOUND VELOCITY MEASUREMENTS

AUTHORS: ROBERT S. HIXSON (M-6)  
ROBERT G. MCQUEEN (M-6)  
JOSEPH N. FRITZ (M-6)

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Los Alamos National Laboratory  
Los Alamos, New Mexico 87545



# **THE SHOCK HUGONIOT OF 316 SS AND SOUND VELOCITY MEASUREMENTS\***

**R. S. Hixson, R. G. McQueen, and J. N. Fritz**  
**Los Alamos National Laboratory**  
**Los Alamos, NM 87545 USA**

## **ABSTRACT**

Type 316 stainless steel has been characterized for its high-pressure, shock-wave response. Measurements have been made of shock wave and particle velocity, and of sound velocity. Our preliminary results for shock and particle velocity have been combined with previously unpublished results, and an overall fit made. Sound velocity results show a discontinuity that is attributed to shock induced melting.

## **INTRODUCTION**

Accurate high pressure, shock wave data are important for a variety of reasons. Such data can provide high pressure standards, can aid in modeling material behavior, and can be used to detect high pressure phenomena, such as melting. For the above applications it is important to have accurate Hugoniot data. It is possible to reduce such data to room temperature isotherms,<sup>1</sup> providing valuable comparisons with static results.

Shock wave compression experiments were performed on type 316 stainless steel in order to characterize it as an impactor material. For this material to be useful in experiments measuring sound speeds, the release wave velocities were also measured. Type 316 stainless steel is an attractive impactor material because it can be accelerated to high velocities using high explosives techniques.

## **EXPERIMENTAL DETAILS**

Type 316 stainless steel is an iron alloy with the following minor components:  $\sim .08\%$  C,  $\sim .2\%$  Mn,  $\sim .1\%$  Si,  $16-18\%$  Cr,  $10-14\%$  Ni, and  $2-3\%$  Mo, according to the Metals Handbook.<sup>2</sup> Average sample density was taken to be  $7.96 \text{ gm/cc}$  with a few tenths of a percent scatter from sample to sample. Two complementary experimental techniques were used for this work.

### *Hugoniot Measurements*

Target assemblies consist of circular step targets with self-shorting shock-arrival pins at two thicknesses, and at the center. This combination of pins allows flyer bow and tilt corrections to be made.<sup>3</sup> Data were taken using the two-stage, light-gas gun facility at the Los Alamos National Laboratory. This gun is capable of accelerating impactors to velocities between 3.5–8 km/s. All experiments were done using symmetric impacts. Impactor velocities were measured both with a flash x-ray system, allowing a best-case accuracy of 0.1%, and a time interval system with best case accuracy of 0.5%. The arrival pin technique for measuring shock velocities is quite accurate (<1%) if all pins function reliably. All experiments shown here had all thirteen pins working correctly.

Our new Hugoniot data for 316 stainless steel are shown in Figure 1. Also shown in Figure 1 are older unpublished Hugoniot data using high explosive techniques. The best overall fit to the data in Figure 1 is given by:

$$u_s = 1.544u_p + 4.464 \quad (1)$$

for  $0.54 < u_p < 3.32$  mm/ $\mu$ s.

The least squares fit of the data is 0.76%, with a worst case deviation of 1.65%. There is still a need to extend this data to higher pressure; this work is in progress. In Figure 2 the Hugoniot curve is plotted in the pressure-volume plane.

### *Sound Velocity Measurements*

Sound velocities are measured using a rarefaction overtake technique.<sup>4</sup> This method involves using thin impactors to introduce a “short shock” into the target. The shock wave in the target is followed by a release that eventually overtakes it and reduces pressure. The overtake point is determined using an optical technique for several target thicknesses, allowing sound velocity behind the shock to be calculated. This technique is quite accurate, allowing sound velocity to be determined to better than 1% for best case conditions. These experiments were performed using both the two-stage gas gun facility mentioned above, and using explosively driven flyer plate techniques. Where data taken with these two complementary techniques overlap, they agree to well within experimental error. Experiments done with explosives allow much larger diameter target assemblies. For these experiments 12 inch diameter flyer plates were used. This allows greater target thicknesses than possible with two-stage gas gun targets. The fitted Hugoniot, Eq. (1), has been used

in the sound-velocity calculations.

Our results for sound velocity are shown in Figure 3, plotted against density. There are two linear segments with a sound velocity discontinuity occurring at  $\rho \sim 12$  gm/cc. This corresponds to a pressure of about 227 GPa, and is presumably due to melting. Also shown in Figure 2 is a calculated bulk sound velocity curve, which agrees well with the data above  $\rho = 12$  gm/cc. Bulk sound velocities were calculated using the  $\rho\gamma = \text{constant}$  assumption, and an initial  $\gamma$  of 2.17.

For pure iron, Brown and McQueen<sup>5</sup> observed two breaks in the sound velocity curve, corresponding to a solid-solid transition, and melting. The one break observed in the sound velocity curve for 316 stainless steel falls in between the two breaks that were seen in pure iron in pressure. However, the stainless sound velocity break and the first break in the iron curve occur at very near the same density. This may be coincidence, since all indications are that the one observed break in the stainless sound velocity curve is melting. This interpretation should be considered to be preliminary, and work is ongoing on this problem.

Linear fits have been made to the two observed branches of the stainless steel sound velocity density curve. The lower pressure (solid) region is best fit by

$$c = 0.933\rho + 1.374 \quad , \quad (2)$$

with an average deviation of 0.71%, for  $10.569 \leq \rho \leq 11.854$  gm/cc, and with  $c$  in km/s. The higher pressure (liquid) region is best fit by

$$c = 1.153\rho + 4.384 \quad , \quad (3)$$

with an average deviation of 0.39%, for  $11.96 \leq \rho \leq 12.5$  gm/cc, and with  $c$  in km/s.

The melting point we observe for 316 stainless is qualitatively consistent with the room pressure melting behavior when compared to that of pure iron. The melting point of iron at 1 atm is taken as 1810 K, and that of 316 stainless is considerably lower, given by the Metals Handbook<sup>6</sup> as 1644–1783 K.

## DISCUSSION

New data have been obtained for shock and particle velocity in type 316 stainless steel. Symmetric impacts were obtained using a high performance, two-stage gas gun, allowing accurate measurements to be made of impactor velocity, and shock velocity corrected for impactor bow and tilt.

Sound velocities have been measured over a wide pressure range using an optical analyzer technique. Results show a linear variation of sound velocity with density followed by a discontinuity in sound velocity at 227 GPa. After the drop in sound velocity at 227 GPa, sound velocity again increases linearly with density, but with a different slope than observed in the lower pressure range. We interpret this sudden drop in sound velocity at 227 GPa to be the onset of melting. This is supported by the agreement of the upper segment of our  $c - \rho$  plot with calculated bulk sound velocities.

Type 316 stainless was characterized for sound velocity in order to use it as an impactor material for other experiments. It appears that it will be able to replace pure iron for this use, effectively filling this shock impedance value, but avoiding the solid solid phase transition present in iron. Having a simple sound velocity behavior with pressure is a desirable feature for an impactor used in sound velocity experiments.

### *Acknowledgment*

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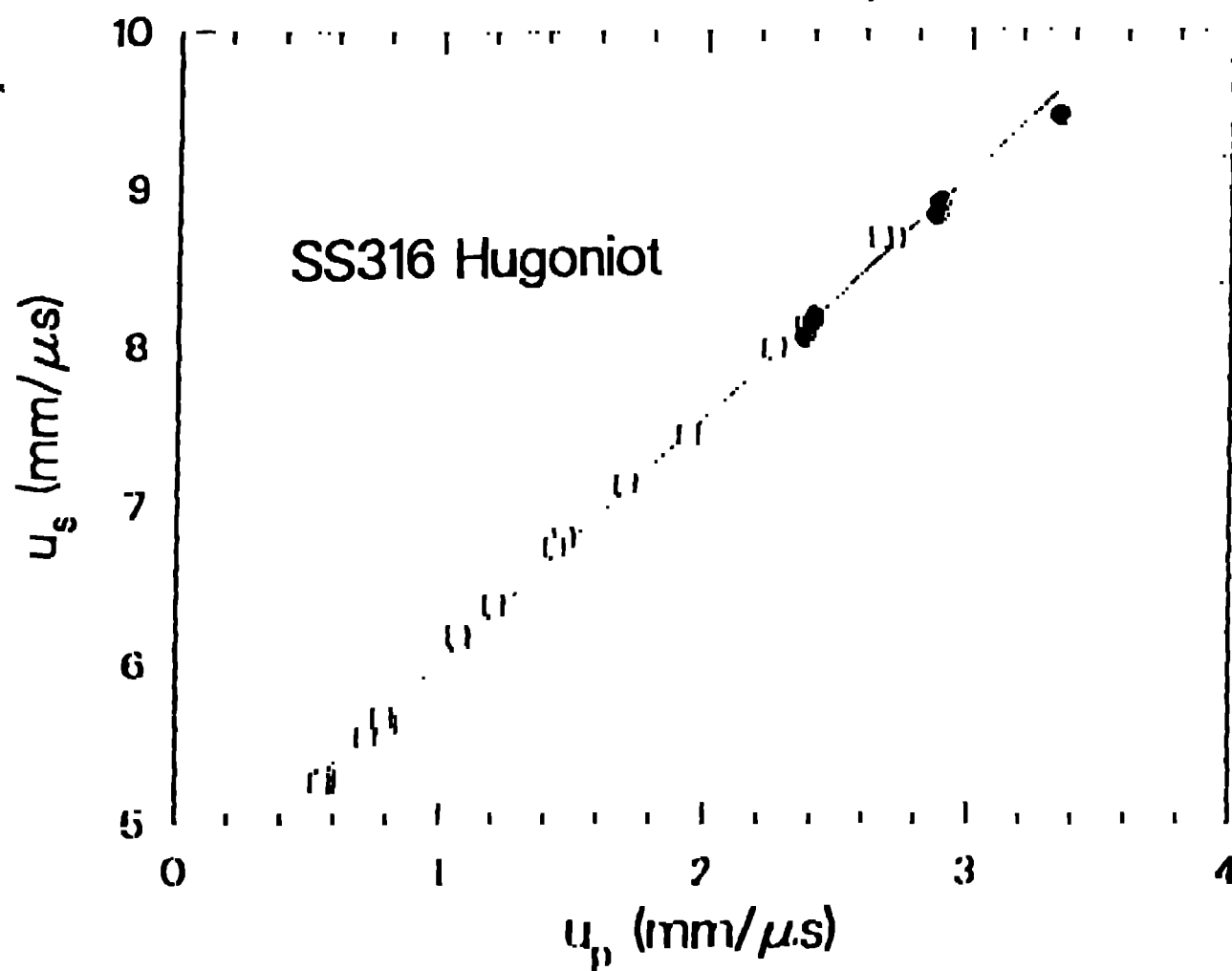


Figure 1. Open squares are explosive experiments taken on an aluminum baseplate. Filled circles are symmetric impact experiments performed with a gas gun.

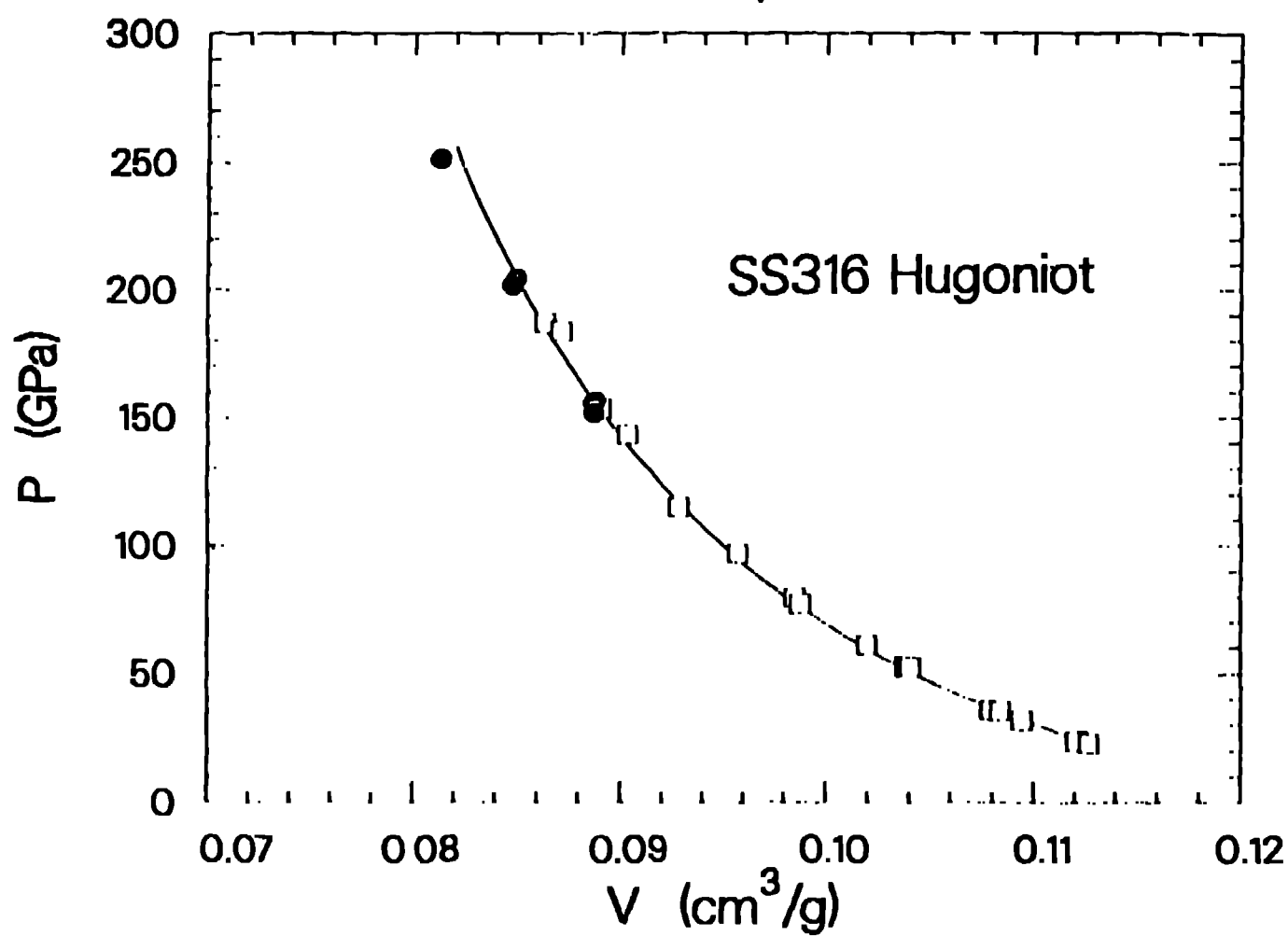


Figure 2. Hugoniot for type 316 stainless steel shown in pressure-volume coordinates.

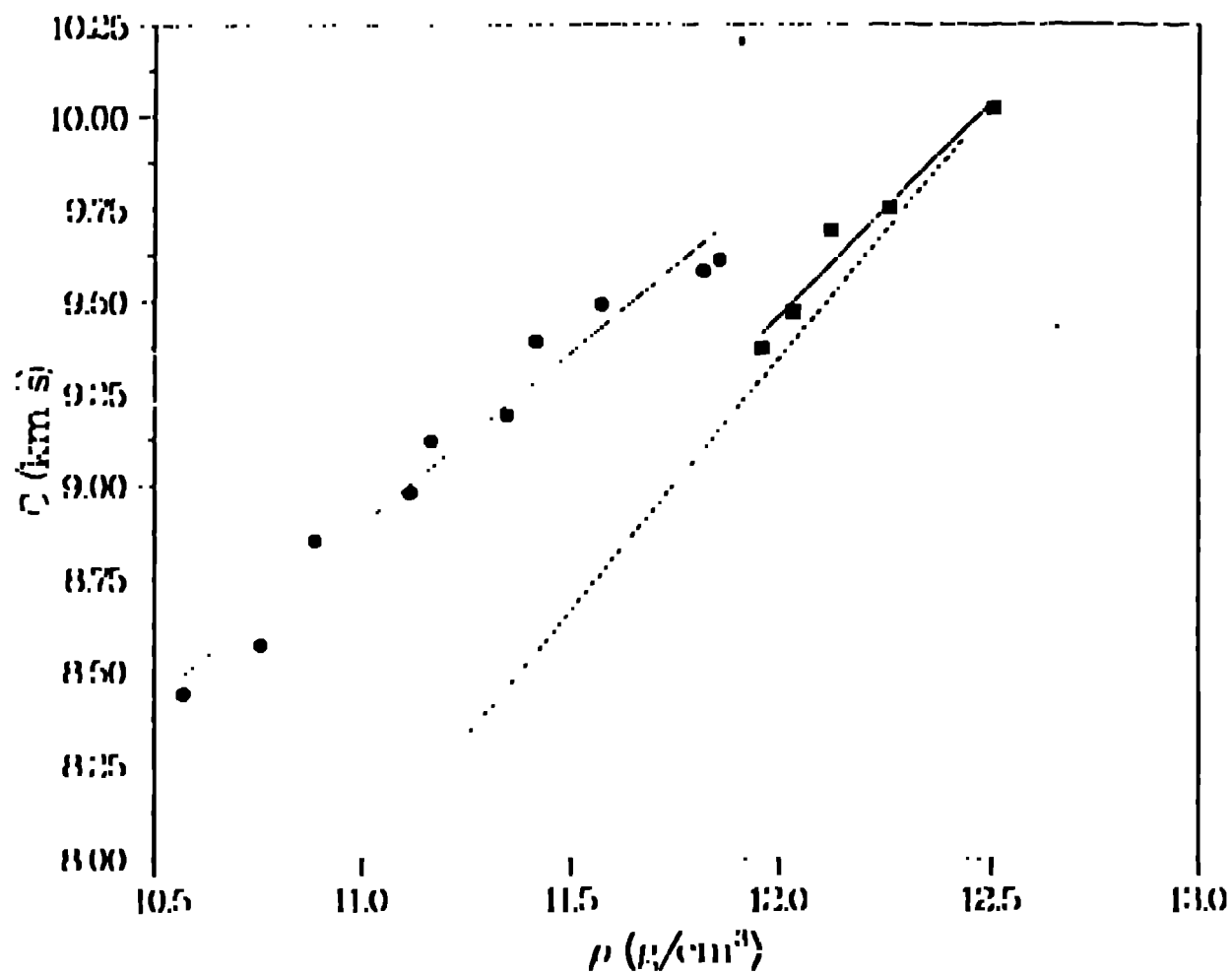


Figure 4. Sound velocities for type 316 stainless steel shown plotted against density. Solid lines are fits to the data, and the dashed line is the calculated bulk sound velocity curve.